Elastic Force Feedback with a New Multi-finger Haptic Device: The DigiHaptic

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Abstract. This article presents a classification of and comparison between isotonic, isometric and elastic devices. It then introduces the DigiHaptic, a new three degrees of freedom multi-finger force feedback device, and its place in the device classification is proposed. Two notable features of the DigiHaptic are the decoupling of the degrees of freedom and the correlation between fingers and objects movements. Finally two force feedback solutions using the DigiHaptic in elastic mode are proposed for rate control in open and closed workspaces.

1 Introduction

The aim of virtual reality is to immerse the user in another world by simulating all his senses of which sight, hearing and touch are the most significant. Where a computer screen and loudspeakers provide image and sound, the haptic device allows interaction between the user and the virtual world through force and touch feedback. The development of high technology graphics cards and graphics software together with high quality sound make it difficult for the user to distinguish the difference between reality and fiction. Haptic devices still need further development to reach the same level of realism.

Devices for remote control appeared in the 1950s with master-slave telemanipulation where the operator controls a master arm that transmits his command to a remote slave [1]. Then force feedback has been introduced to feel on the master the forces exerted on the slave. With computers, two dimensional devices like the computer mouse appeared to remote control the screen pointer and the work done in telemanipulation and force feedback was reapplied to three dimensional (3D) worlds.

Two dimensional haptic devices were the first to appear with the force feedback joystick (for example: Microsoft SideWinder force feedback joystick [2]) and the force feedback mouse (WingMan force-feedback mouse from Logitech [3]). Force feedback devices with three degrees of freedom or more are less common. There are a couple of prototype devices and a few commercialized ones that are expensive because of their complex mechanisms. By studying these devices, we can note that force feedback is used primarily with position control devices, where the position of the device is tracked to correspond with the position of the virtual object being manipulated. In these conditions the forces applied to the object are reproduced on the force feedback device to provide a realistic feeling of the object being handled.

The concept of force feedback with elastic devices, where the device outputs raw forces calculated by the virtual environment, has been applied experimentally using the newly developed multi-finger haptic device called the DigiHaptic [4], which has the capacity for rate control in elastic mode with force feedback.

This article presents a classification for and a comparison of devices with two and more degrees of freedom. The DigiHaptic is then described in Sec. 3 and its place in the classification is assigned. Finally elastic force feedback using the DigiHaptic in master and slave mode is described and then contrasted.

2 Device Classification

The human limb (superior and inferior) can send and receive information through either displacement/rotation or force/torque. Correspondingly, an isotonic device connects the human limb and computer through movement while an isometric device does this through force/torque.

Devices can be classified in three main categories, namely isotonic, isometric and elastic as de-

scribed by Zhai in [5] from whom we have taken the definitions of these categories.

2.1 Isotonic Devices

Isotonic devices refer to devices operated with displacement. They are free moving devices. According to Collins English dictionary and thesaurus 1994, isotonic means in physiology "of two or more muscles having equal tension". An isotonic device should have zero or constant resistance. They can be absolute or relative depending on the displacement sensor used and the mechanical design. For absolute isotonic devices a unique position of the pointer on the screen corresponds to a position of the device. So the pointer position in the virtual workspace is set at the start of manipulation, depends on the device position and does not require pre-calibration. Nevertheless the operating range in the virtual workspace is limited to the device boundaries. The relationship between the operating range and the device boundaries is a linear function (1) where $Op_{x,y,z}$ is the operating distance in centimeters at the screen along x, y and z axis, $D_{x,y,z}$ is the device operating range in centimeters along x, y and z axis and $sensitivity_i$ is a constant coefficient that is called the sensitivity factor. To keep an homogeneity in all directions and not disturb the user, usually $sensitivity_x = sensitivity_y = sensitivity_z$.

$$Op_i = sensitivity_i \, D_i \ , i = x, y, z \qquad (1)$$

We present an illustrative example for (1). Equation (2) presents the sensitivity factor (*sensitivity*) for the computer mouse that depends on the screen size in inches ($screen_{size}$), screen resolution along the screen width in pixels ($screen_{res}$) and mouse resolution in dpi ($mouse_{res}$).

$$sensitivity = \frac{4}{5} \frac{mouse_{res} \, screen_{size}}{screen_{res}} \qquad (2)$$

For screen sizes from 15" to 21", screen resolutions from 640×480 to 1280×1024 and a mouse resolution of 400 dpi (which is the default setting on most computers) , the sensitivity goes from 3.7 to 10.5. This sensitivity gives for example the number of centimeters the computer pointer moves for each centimeter of mouse displacement.

For absolute isotonic devices, the sensitivity is adjusted depending on the user's skill and the limb used to handle the device due to limb displacement resolution [6]. The sensitivity is not the same if the device is moved with the fingertips or the forearm.

In contrast, acceleration of the pointer is possible for relative isotonic devices. The distance on the screen covered by the pointer for a given movement of the pointing device (e.g., the mouse) is increased by a factor called the acceleration. The mouse will go into accelerated mode if the pointer is made to make a rapid movement on the screen larger than a given threshold distance. This mode is only possible for relative isotonic devices as there is a no correlation between the absolute pointer position on the screen and the absolute device position.

From the user's point of view, this acceleration feature allows for slow, precise pointer motions over small distances and rapid motions across the screen with a short but quick motion of the mouse. Large acceleration values and small threshold values may make the pointer motion too jerky to be useful, as it will always move very quickly.

Relative devices can be declutched when the limits of the device workspace are reached in order to re-center them without moving the screen pointer.

2.2 Isometric Devices

Isometric devices are pressure and force devices. They sense force but do not perceptibly move. According to Collins English dictionary and thesaurus 1994, isometric means "having equal dimensions or measurements" and in physiology is defined as "of or relating to muscular contraction that does not produce shortening of the muscle". Isometrics means "physical exercise involving isometric contraction of muscles".

In practice, the user applies a force on the device that is measured and used to control the rate of movement of the screen pointer. The velocity is proportional to the applied force. Examples of isometric devices are the TrackPoint from IBM [7] for two dimensional environments and the SpaceBall from 3DConnexion [8] for 3D environments.

2.3 Elastic Devices

Elastic devices are between isometric devices (infinite resistance) and isotonic devices (zero or constant resistance) because they have varying resistance to force. When this resistance increases with displacement the device is elastic, when it increases with velocity the device is viscous and when it increases with acceleration, the device is inertial.

Elastic devices behave like isometric devices as the user applies a force on the device and to each force there is a corresponding velocity. The difference is that the device moves and a force proportional to its displacement is generated to always return it to a neutral position.

2.4 Comparison

Zhai and al. have performed several studies comparing a hand tracking glove (an isotonic con-

troller) with a Spaceball to dock and align a 3D cursor with a 3D target [9],[10]. In different conditions, each control device was used to control either velocity or position of the cursor. They found that for controlling velocity, the isometric device was superior to the isotonic device, and that the isotonic device was better for controlling position. They also compared isometric and elastic devices for velocity control. They found that subjects performed better with the elastic velocity controller than with the isometric controller and hypothesized that this was true because the elastic device provides better control feel.

The choice between isotonic, isometric and elastic depends on the type of task to be performed. There are two main categories of tasks that can be accomplished by the user: manipulation tasks, where the user handles objects in the virtual world with rotations and translations, and navigation tasks, where the user navigates within the virtual world. Manipulation tasks, like daily life tasks, require precise and fine movements that can be executed with isotonic devices as there is a direct control of position. The disadvantage is that all human movements are reproduced (voluntary as involuntary). Navigation tasks require speed control to perform large displacements. So they fit well with isometric and elastic devices where the speed is directly controlled through small displacements without exhausting the user. Moreover isometric and elastic devices act as a low pass filtering through the integration of speed and so suppress high frequency involuntary noises.

There is force feedback when the forces felt by the user relate to properties of the virtual objects. It does not include forces sent by the device unrelated to the virtual environment. In that sense, an isometric device where the device generates a reaction force equal to the one applied by the user is not a force feedback device. There is force feedback, however, when the device provides energy to the user to produce a displacement of the device with actuators. Thus force feedback can be generated with isotonic and elastic devices but not with isometric ones.

With isotonic devices, the maximum operating range is limited unless clutching is used. Isometric devices have an effectively unlimited operational range because they are auto-declutching devices. These ranges respectively correspond to closed and open workspaces.

Closed workspaces have a limited operating volume where the camera point of view on the objects is usually fixed. Theses workspaces are not suited for navigation but for manipulation with absolute isotonic force feedback devices like the PHANToM [11]. Examples of such workspaces are Spin [12] and Spore [13] developed in the LIFL. Spin is a 3D workspace where users can work together on virtual objects with no force feedback. Interaction metaphors have been developed to interact efficiently with these objects. Spore is a physical engine able to render objects properties and forces according to physical equations and using either penality based method or "god-object" for collision detection.

Opened workspaces have an infinite operational range and the camera follows the pointer. Examples of such workspaces are visits to virtual museums [14] or doom-like games. Absolute isotonic device cannot be used in this type of workspace. Although relative isotonic devices can be used, we have found that isometric and elastic devices are better because declutching the device decreases user satisfaction.

3 The DigiHaptic

3.1 Description

The DigiHaptic [4] is a three degrees of freedom ground-based device. The device is comprised of three levers associated with the thumb, forefinger and ring finger as shown in figure 1. Each lever is associated with a DC motor to provide force feedback. The design, hardware and control are discussed in detail in [15] .

A QNX RTOS PC at 350MHz controls the device in impedance at 1000Hz in real time. An analog digital card on the QNX PC reads levers angular positions and sends instructions to the motors. Position and velocity of the lever are both sent through the local network to a Windows PC running the virtual environment. The levers' inertia and few viscous frictions are compensated by the command. Forces from the virtual environment are received from the windows PC and sent to the levers (in isotonic and elastic modes). Predefined behaviors such as springs (isometric and elastic modes), damping or bumps are directly operated by QNX PC.

The user puts his hand on the higher part of the device in an ergonomic way and can handle the three levers simultaneously or separately but always independently. Each lever has 120° of freedom and 20mm of radius, that is a compromise between finger's and lever's freedom (i.e. the more the lever's radius, the less possible lever angle displacement). Maximum force was calibrated to be 2N. This appears to be sufficient to render stiff walls at fingertips.

3.2 Modes of Use

The DigiHaptic can be used in isotonic and elastic mode with force feedback and isometric mode.

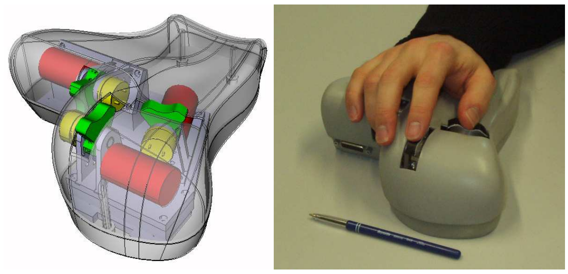

Fig. 1. The DigiHaptic with its three levers actuated by motors and the way the user puts his hand on it.

In each mode there is a relationship between finger and object movement. Objects are translated according to the width of the screen (x axis) with the thumb, the height of the screen (y axis) with the ring finger and the depth of the screen (z axis) with the forefinger. Rotations are done around the x, y, z axes with the corresponding levers. During collision detection, forces calculated by the virtual environment are projected on the x, y, z axes and each projection is sent to the corresponding lever.

In addition, due to hand morphology constraints (male and female) a user can use up to 60° of each lever's freedom, that is to say 20 mm $\times \frac{pi}{3}$ rad $\approx$ 20 mm which corresponds for a device sensitivity of 5 (see Sect.2.1) to a maximum workspace volume of 10 cm × 10 cm × 10 cm.

The DigiHaptic can be used in isometric and elastic mode for rate control, where elastic mode provides a better sense of manipulation compared to isometric (Sect. 2.4). In isometric mode, a high stiffness is applied by the motor which generates low displacements around a reference position. The utilisation is like that of the SpaceMouse [16]. In elastic mode, low to medium stiffness is applied to the levers. The user feels a force proportional to the lever's displacement. The pointer speed is proportional to the force so proportional to the lever displacement. We have empirically tested the proportional relationship between pointer speed (P_s) and the lever displacement (θ). The proportional coefficient (c) was fixed in order to get a small speed for a small lever displacement (3). Nevertheless for bigger displacements, the speed was still too low compared to the excepted one by the user, giving an exhausting feeling to the user. To get a low speed for a small displacement and at the expected one by the user for larger displacements, a third power polynomial appears to be satisfactory (4).

$$P_s = c\,\theta \quad (3)$$

$$P_s = c_1\,\theta + c_2\,\theta^2 + c_2\,\theta^3 \quad (4)$$

As the lever's angle is never exactly equal to zero due to friction forces, the pointer speed is never null. We set a deadband surrounding the zero position to avoid this. The deadband (θ_0) can be calculated from the friction force (F_f) and the lever's stiffness (k_0) as follows:

$$\theta_0 = \frac{F_f}{k_0} \quad (5)$$

Moreover force feedback for elastic mode is proposed to render force from the virtual environment. We will discuss it in Sec. 4.

3.3 DigiHaptic Capabilities

The DigiHaptic can be used in open and closed workspaces in isotonic or isometric mode. Moreover the design reduces the user's exhaustion by using small movements. It is also possible in isometric mode or isotonic to drop the levers to do a pause whilst in operation. The virtual operational range in isotonic mode is not high but still sufficient for most closed workspaces and the choice between isotonic and isometric depends mainly on the task category to be performed (manipulation or navigation).

First empirically experiments are encouraging because they show that users are able to use the device after a short training time without difficulty or cognitive conflicts. Moreover the force vector projection on each lever in isotonic mode doesn't disturb the user in fingers motivity or cognitive behaviour.

Additionally the DigiHaptic has the ability to be used in elastic mode with force feedback.

4 Elastic Force Feedback

Usually force feedback is limited to isotonic devices in closed workspaces. For open workspaces where elastic devices are better, we propose an elastic force feedback to render forces from the virtual environment. It has to be stated that Lecuyer and al. have showed that it is possible to provide pseudo-haptic force feedback with isometric devices [17].

It has to be noticed that force feedback joysticks allow to render forces. However these devices are used in games with high level force feedback [18]. This means that models are preprogrammed in the device with parameters such as duration or magnitude of the effect and the application sends to the device an effect to be applied. There is currently no way to send raw forces to force feedback joysticks.

Elastic force feedback has been experimented on the *Magic Wrist* used for fine/coarse positioning in teleoperation [19]. This device allows low

displacements of the end effector and is used in both isotonic/elastic modes. Isotonic mode is defined around the end effector central position and elastic mode is defined at the device boundaries. When the user is in elastic mode with rate control and receives a force from the slave, the end effector is moved in the isotonic range and forces are felt in isotonic mode.

We present hereafter elastic force feedback for the DigiHaptic that could be extended to elastic devices in general. We defined two modes (master and slave) that can be applied to elastic force feedback .

4.1 Introduction

With the DigiHaptic in elastic mode, the force F at the end of the lever is proportional (k_0) to its displacement (the lever's angle θ) as written in (6). A reference position or neutral position where $\theta = 0$ is usually set at equal distances of the levers limits. Thus the lever is always brought back to the neutral position.

$$F = k_0\,\theta \tag{6}$$

To introduce the forces generated by the virtual environment, it is possible either to embedded them in the stiffness to get a stiffness function of force (7) or to add a term function of force next to the elastic term (8).

$$F = function(force) \times \theta \tag{7}$$

$$F = k_0\,\theta + function(force) \tag{8}$$

The equations (7) and (8) describe the two modes we named master and slave.

4.2 Master

This mode is when the stiffness is a function of force. The following results are the application of the work on a velocity controller with force feedback stiffness control applied on an excavator to fell the forces exerted on the bucket [20].

The requirements for such a function (7) are as follows:

- Need to keep a constant stiffness coefficient to keep a stiffness when there is no force.
- Positive force should increase the stiffness and negative ones should decrease it. Force from virtual environment is defined as positive when it opposes pointer motion for θ positive.
- The speeder the pointer arrives on an obstacle, the more important the force variation should be.

So the function in (7) needs to have a constant term summed with a term depending on the sign of the rendered force and proportional to the distance between the actual and neutral lever's positions . Let's be k as the variable rigidity, k_0 the constant rigidity, f the force generated by the virtual environment and a a scale factor between the virtual environment and the device depending on the device. F is the force at the end of a lever and θ the position angle of the lever.

$$k = k_0 + a\ sgn(\theta)\,f \tag{9}$$

$$F = (k_0 + a\ sgn(\theta)\,f)\,\theta \tag{10}$$

The term $a\,f$ is the easiest law that can be defined. Indeed it is possible to propose a law in logarithmic or exponential terms to play with qualitative feelings depending on the task.

With equation (10), the pointer can't move when the levers are in a neutral position even when forces are applied on the pointer so the screen pointer position depends solely on the user intention. That's why we called it master mode.

The same deadband as defined in 3.2 has to be set.

4.3 Slave

The slave mode consists in adding a term to the elastic one. This term has to be independent of θ or it would be the same as the master mode. So we are proposing a term proportional to the force generated by the virtual environment (11). $a\,f$ is the same force sent to the device in isotonic mode so (11) is both an elastic and an isotonic term.

$$F = k_0\,\theta + a\,f \tag{11}$$

As in master mode $a\,f$ is the simplest term for the slave mode but refinements depending on the task to be performed together with the magnification or attenuation of the forces generated by the virtual environment can be defined.

The pointer can move when the neutral position is reached and forces can be exerted on the pointer, thus we called it slave mode.

The constants k_0 and a have to be chosen so as to get a good qualitative feeling and a good ratio between the elastic effect and the force feedback.

a depends on the virtual environment. If the virtual environment calculates huge forces the a term will be low (e.g. aircraft manipulation) and it will be high if the virtual environment calculates low forces (e.g. molecules manipulation). k_0 has to be chosen in order to be able to render forces from the virtual environment when the lever boundaries are reached.

The same deadband as defined in 3.2 has to be set.

4.4 Comparison Between Master and Slave Modes

Having discussed the specifications of the master and slave modes, we can draw out the following main features:

- In *master mode*, forces are mainly felt in the main direction on the finger having the highest speed. A same force is not rendered in the same way whatever the lever angle is. This can be used for navigation tasks.
- In *slave mode*, the user has a smooth feeling because forces are equally rendered on the three levers whatever the lever angle is. This mode is better for manipulation tasks.

5 Conclusion and Future Work

We have presented a device classification divided into isotonic, isometric and elastic. We have seen that the DigiHaptic can be used in all these modes. The device classification has then been paralleled with open and closed workspaces and it has been showed that only certain classes of devices can be best used for particular combinations of workspace type and task category. Again the DigiHaptic can be used in both types and categories. Finally the extension of elastic force feedback into master and slave modes has been proposed and defined.

For the future works, we plan to create software applications to evaluate experimentally each situation in order to find the qualitative and quantitative limits of each mode.

The DigiHaptic is going to be tested in other kind of applications such as navigation situation where the camera point of view is moved in 3D environments. The user is there able to orientate the camera with two levers and move it with the third one. Force feedback using the described elastic master force feedback will be tested to feel walls collisions.

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